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## Critical Current Test of Liquid Hydrogen Cooled HTC Superconductors under External Magnetic Field

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### Abstract

High-Tc (HTC) superconductors including  $\text{MgB}_2$  will show excellent properties under temperature of Liquid Hydrogen ( $\text{LH}_2$ :20K), which has large latent heat and low viscosity coefficient. In order to design and fabricate the  $\text{LH}_2$  cooled superconducting energy devices, we must clear the cooling property of  $\text{LH}_2$  for superconductors, the cooling system and safety design of  $\text{LH}_2$  cooled superconducting devices and electro-magnetic property evaluation of superconductors ( $\text{BSCCO}$ ,  $\text{REBCO}$  and  $\text{MgB}_2$ ) and their magnets cooled by  $\text{LH}_2$ . As the first step of the study, an experimental setup which can be used for investigating heat transfer characteristics of  $\text{LH}_2$  in a pool and also in forced flow (circulation loop with a pump), and also for evaluation of electro-magnetic properties of  $\text{LH}_2$  cooled superconductors under external magnetic field (up to 7 T). In this paper, we will show a short sketch of the experimental set-up, practical experiences in safety operation of liquid hydrogen cooling system and example test results of critical current evaluation of HTC superconductors cooled by  $\text{LH}_2$ .

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**Keywords:** liquid hydrogen; HTC superconductor; critical current

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## 1. Introduction

Hydrogen related technology is now developing as one of the important solutions for innovative energy infrastructure for reduction of CO<sub>2</sub> emission. Future clean energy system should be a hybrid system with combination of electric power system and hydrogen energy supply chain. Liquid hydrogen may be a candidate for an energy carrier in the hydrogen supply chain, but liquefaction energy is not so small. If liquid hydrogen is used as a coolant for High-Tc (HTC) superconducting devices, which might be key components for the hybrid energy system, the cryogenic energy can be used effectively. Hydrogen can be used for not only coolant of the superconducting power devices but also energy storage for long period in electric power system.

By now, HTC superconductors, such as REBCO and BSCCO are usually cooled by liquid nitrogen (77K), but will show excellent properties under temperature of 15-40K. Liquid Hydrogen (LH<sub>2</sub>:20K), which has large latent heat, low viscosity coefficient, is expected as an excellent coolant.

However, there has been a lack of extensive heat transfer data of LH<sub>2</sub> in forced flow condition for superconductor cooling. And, due to handling difficulties of LH<sub>2</sub>, there are only few papers on the properties of LH<sub>2</sub> cooled superconductors, especially under external magnetic field. In order to design and fabricate the LH<sub>2</sub> cooled superconducting energy devices, we must clear the followings.

1. Cooling property of LH<sub>2</sub> for superconductors
2. Cooling system design of LH<sub>2</sub> cooled superconducting devices
3. Safety design of LH<sub>2</sub> cooled superconducting device
4. Electro-magnetic property evaluation of superconductors (BSCCO, REBCO and MgB<sub>2</sub>) and their magnets cooled by LH<sub>2</sub>
5. Practical experiences in safety operation of LH<sub>2</sub> cooling system

As the first step of the study, an experimental setup which can be used for investigating heat transfer characteristics of LH<sub>2</sub> in a pool and also in forced flow[1],[2], and also for evaluation of electro-magnetic properties of LH<sub>2</sub> cooled superconductors under external magnetic field (up to 7 T) was designed and made[3]. We reported the test results on the critical current of PIT-MgB<sub>2</sub> short wire cooled by LH<sub>2</sub> under magnetic field up to 1.2 T [4].

In this paper, we will show a short sketch of the experimental set-up, and example test results of critical current evaluation of IMD(internal Magnesium Diffusion)-MgB<sub>2</sub> superconductor cooled by LH<sub>2</sub> under magnetic field up to 5.5T .

## 2. Experimental Apparatus

### 2.1. Experimental cryostat for critical current test of LH<sub>2</sub> cooled superconductor under magnetic field

Fig.1 shows the schema of LH<sub>2</sub> test cryostat. The cryostat (61L) has 309.5 mm inner diameter and has 2122 mm height. The LH<sub>2</sub> Cryostat is set coaxially in a bore area of liquid helium (LHe) cryostat (175L) in which an Nb-Ti superconducting magnet (112.35H, 175A) cooled by LHe is equipped. Magnetic field of the test area with LH<sub>2</sub> can be set to 0-7.0 T. Pressure in the LH<sub>2</sub> test cryostat can be set to 0.1-2.0 MPa by use of the feed hydrogen gas line. The bulk-liquid temperature can be changed by use of the sheathed heater equipped at the bottom of the cryostat. Electric current can be applied to the test sample up to 800 A by use of DC power sources. Three current lead through the top flange are covered with blanket (corrugated pipe) pressurized slightly positive by nitrogen gas in order to prevent an explosion failure.

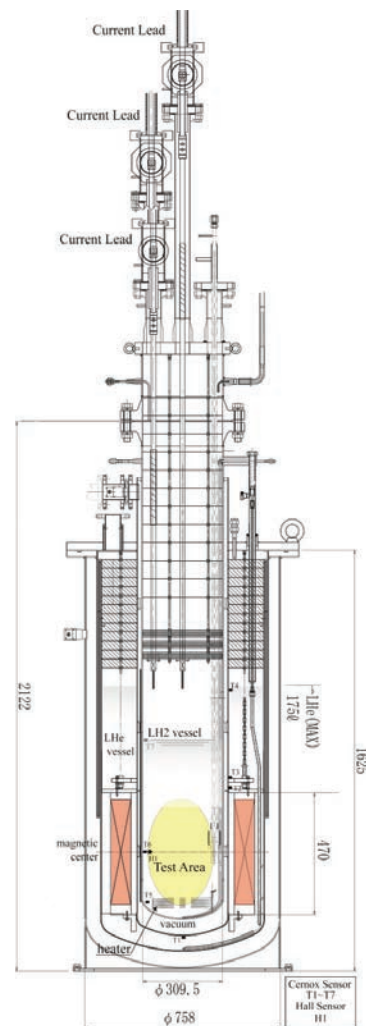


Fig.1 Experimental cryostat for critical current test of LH<sub>2</sub> cooled superconductor under magnetic field.

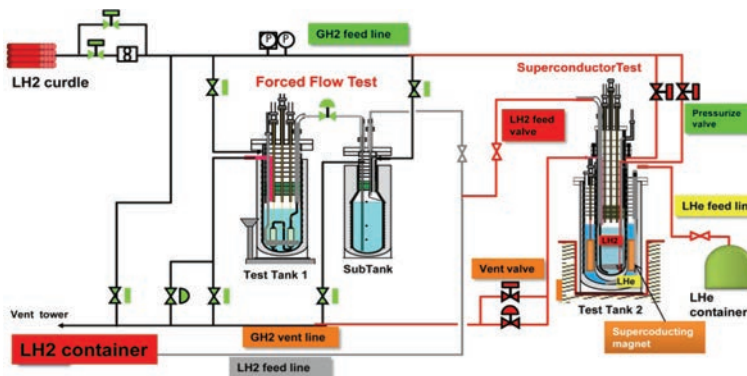


Fig.2 Experimental system

and a LH<sub>2</sub>-LHe hybrid test tank2 described before, a transfer tube with a flow control valve between the test tank1 and the sub tank, a gaseous hydrogen feeding line from compressed hydrogen clustered cylinders and vent lines.

The experimental system is installed in an explosion-proof laboratory, in which two hydrogen leak detectors are equipped on the ceiling. During the experiment, the experimental system is remotely operated with optical communication network in a control room 71 m far from the laboratory.

### 3. Critical Current Measurement Test

#### 3.1. Test MgB<sub>2</sub> wire

The schema of the Fe sheathed IMD MgB<sub>2</sub> wire is shown in Fig. 3. The test MgB<sub>2</sub> wire was single filament wire fabricated by IMD process by Kumakura Group (NIMS). Coronene (C<sub>24</sub>H<sub>12</sub>) was added to the boron powder in a fabricating process. The amount of coronene added to boron powder was 5 at%. The test sample wire was 40 mm in length, 0.614 mm in diameter.

The distance between current leads was 30 mm, and that between voltage taps were 10 mm. The outer voltage tap was used for the burn-out detector. The copper plates were soldered at both end of the test wire, and the copper current leads were soldered on the copper plates. Additionally, the BSCCO power leads were soldered at both end of the test wire in order to avoid the joule heat generation from the power leads. The voltage taps were soldered on the sample surface. The test sample was set in the cryostat with its length direction horizontal. The plate made of FRP was set close to the test wire in order to avoid deformation caused by Lorentz force.

#### 3.2. Experimental procedure

The test sample was set in the center of the test area of the cryostat immersed in LH<sub>2</sub>. The bulk-liquid temperature was set to 21, 24, 27 and 29 K with the pressure of 0.1, 0.3, 0.5 and 0.8 MPa, respectively. All tests were carried out under the saturated condition. The magnetic field was set to 0 – 5.5 T by use of the Nb-Ti superconducting magnet cooled by LHe. Electrical current was controlled to increase linearly and shut off automatically to avoid burn-out. Current sweep rate was about 10 A/s.

The critical current ( $I_c$ ) was obtained from the electrical field and transport current ( $E-I$ ) property as shown in Fig. 4 (21 K, 0.1 MPa) with the external magnetic field as a parameter. The critical current was determined under the tap voltage criterion of 1  $\mu$ V/cm. Temperature rise at the voltage appearance is estimated to be slightly small because the nucleate boiling starts immediately under the saturated condition.

#### 2.2. Experimental system

The schematic diagram of the experimental system is shown in Fig. 2. The system is designed to carry out experiments for cooling properties of LH<sub>2</sub> with pool and forced flow, and for electro-magnetic property evaluation experiment of LH<sub>2</sub> cooled superconductors under magnetic field. Major components of the system are a cryogenic test tank1, a cryogenic sub tank (receiver tank),

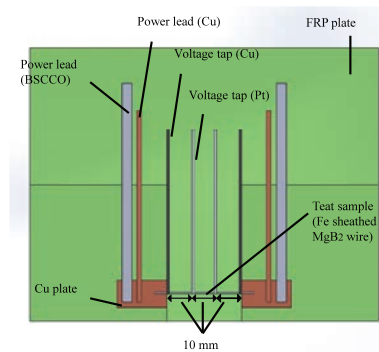


Fig.3 Test sample of IMD MgB<sub>2</sub> short wire and set-up.

Fig. 5 shows critical density versus magnetic field ( $J_c$ - $B$ ) characteristics with various temperatures (solid symbols). The critical current density  $J_c$  was obtained from  $I_c$  divided by cross sectional area of  $\text{MgB}_2$ . The  $n$ -values with each temperature as a function of external magnetic field are shown in Fig.6. The degree of accuracy is insufficient in high magnetic field since the sample wire is rather short. The test area of the experimental set-up has enough large for the longer wire test in the next step.

Open symbols show the results of another IMD- $\text{MgB}_2$  wire measured with conduction cooling reported by Li, et.al [5]. The properties with low- $B$  and large- $J_c$  were able to be evaluated due to the small temperature rise with stable cooling condition immersed in  $\text{LH}_2$ .

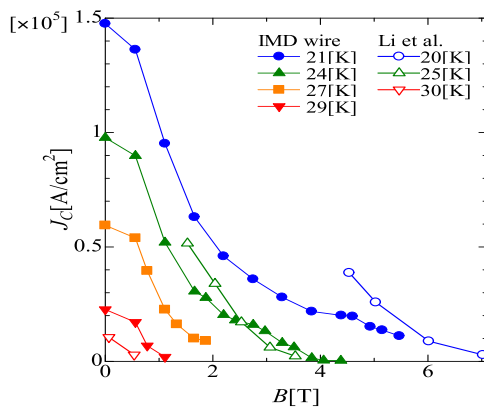


Fig.5 ( $J_c$ - $B$ ) characteristics(solid symbols). Open symbols show the data (another wire) measured with conduction cooling ([5]).

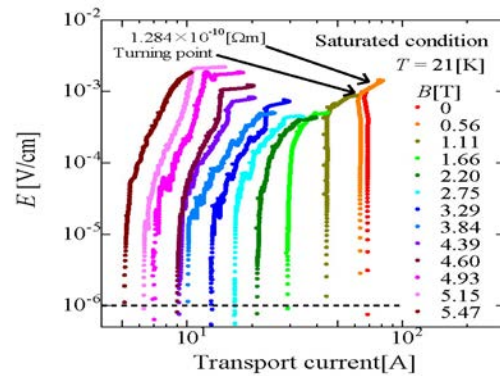


Fig.4 Electrical field and transport current ( $E$ - $I$ ) property (21 K, 0.1 MPa) with magnetic fields as a parameter.

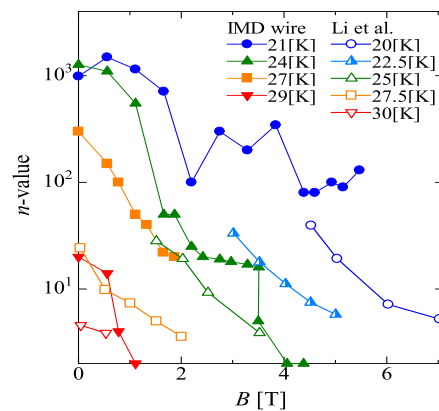


Fig.6 ( $n$ -value- $B$ ) characteristics (solid symbols). Open symbols measured with conduction cooling ([5]).

#### 4. Conclusion

We designed and made an experimental setup which can energize superconducting wires immersed in  $\text{LH}_2$  with the current of up to 500 A under the condition of external magnetic field up to 7 T and pressure up to 1.5 MPa. Using this experimental set-up, critical current tests were carried out using IMD- $\text{MgB}_2$  superconducting short wire under various external magnetic field conditions.

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